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Comparison of the Resonant Frequency in Graphene and Metallic Nano-antennas

Authors:

Ignacio Llatser

Christian Kremers
Bergische Universität Wuppertal

Albert Cabello
Universitat Politècnica de Catalunya

Eduard Alarcón

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Abstract and Figures

The scalability of the resonant frequency in graphene-based nano-antennas (graphennas) and metallic nano-antennas as a function of their length is analyzed. The antenna resonances are obtained by combining the dispersion relation in free-standing graphene and gold layers, respectively, with the resonance condition. Graphennas are found to have a better scalability in terms of their resonant frequency with respect to metallic nano-antennas as their length is reduced to a few µm. These results open up the possibility to build micrometer-sized graphennas that resonate in the terahertz band, at a frequency up to two orders of magnitude below metallic nano-antennas with the same size. Graphennas are thereby envisaged to enable the implementation of wireless communications among nanosystems.

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Comparison of the Resonant Frequency in Graphene

Ignacio Llatser*,†, Christian Kremers†, Albert Cabellos-Aparicio*, Eduard Ala
and Dmitry N. Chigrin†

*Nanonetworking Center in Catalunya (N3Cat), Universitat Politècnica de Catalunya, Jordi Girona 1
Campus Nord, D6-008 08034 Barcelona, Spain
†Theoretical Nano-Photonics Group, Institute of High-Frequency and Communication Technology,
Faculty of Electrical, Information and Media Engineering, University of Wuppertal,
Rainer-Gruenter-Str. 21, D-42119 Wuppertal, Germany

Abstract. The scalability of the resonant frequency in graphene-based nano-antennas (graphennas) and metallic antennas as a function of their length is analyzed. The antenna resonances are obtained by combining the dispersion i in free-standing graphene and gold layers, respectively, with the resonance condition. Graphennas are found to have scalability in terms of their resonant frequency with respect to metallic nano-antennas as their length is reduced to a f These results open up the possibility to build micrometer-sized graphennas that resonate in the terahertz band, at a fre up to two orders of magnitude below metallic nano-antennas with the same size. Graphennas are thereby envisaged to the implementation of wireless communications among nanosystems.

Keywords: light scattering, nano-antenna, terahertz radiation, graphene
PACS: 78.67.Wj, 84.40.Ba, 73.20.Mf

Graphene, a flat monolayer of carbon atoms tightly packed in a two-dimensional honeycomb lattice, has recently attracted the attention of the research community due to its novel mechanical, thermal, chemical, electronic and optical properties [1]. Because of its unique characteristics, graphene is envisaged to enable a plethora of new potential applications, ranging from ultra high-speed transistors [2] to transparent solar cells [3].

Among these, a particularly promising application is graphene-enabled wireless communications. Owing to its ability to support Surface-Plasmon Polariton (SPP) waves [4], graphene is seen as the enabling technology for this emerging field. Indeed, a graphene-based plasmonic nano-antenna, or *graphenna*, (shown in Fig. 1) with lateral dimensions of just a few micrometers is predicted to resonate in the terahertz band [5, 6], at a dramatically lower frequency and with a higher radiation efficiency with respect to their metallic counterparts. By allowing the implementation of antennas with such a small size and a relatively low resonant frequency, graphennas are envisaged to enable wireless communications among nanosystems [7].

With the purpose of studying the novel radiation properties of graphennas, in our previous work [6] we modeled a graphenna as a graphene patch over a dielectric substrate. The graphene patch was characterized by means of its surface conductivity, calculated using the Kubo formalism [8, 9]. Within the random-phase approximation, the surface conductivity of graphene can be rep-

FIGURE 1. Schematic diagram of a graphene-ba monic nano-antenna, or *graphenna*.

resented in a local, Drude-like form. Once the conductivity has been modeled, the relationship the frequency of SPP waves in graphennas wavelength can be found by means of the disp lation of a graphene layer placed on the air-diel terface [10]:

$$\frac{1}{\sqrt{\beta^2 - \frac{\omega^2}{c^2}}} + \frac{\varepsilon}{\sqrt{\beta^2 - \varepsilon\frac{\omega^2}{c^2}}} = -i\frac{\sigma(\omega)}{\omega\varepsilon_0}$$

where β and ω are the wavevector and angular f of the SPP wave, and ε is the dielectric consta

substrate. The resonant frequency f_0 is then obtained by

$$L_{eff} = L + 2\delta L = \frac{\lambda}{\beta} = \frac{c}{2f_0} \quad (2)$$

where the effective antenna length L_{eff} is obtained from the antenna length L and the penetration length of the electric field outside the antenna δL, and c stands for the speed of light.

In this context, in order to quantify the advantages of graphennas with respect to metallic nano-antennas, it is of particular interest to investigate their radiation properties. In this work, we compare the resonant frequency of both antenna types and, in particular, we analyze the scalability of their resonant frequency with respect to their length. Interestingly, we will observe that in the terahertz range not only graphennas resonate at a frequency up to two orders of magnitude lower than metallic nano-antennas, but also the resonant frequency of graphennas increases at a slower pace than that of metallic nano-antennas as their size is reduced.

In order to study the resonant frequency of a metallic nano-antennas, we will consider a patch antenna consisting of a free-standing gold slab placed on an air-dielectric interface, a structure commonly used for plasmonic nano-antennas in the optical range. The resonant frequency of this antenna can be found by analyzing its dispersion relation, given by the following expression [11]:

$$\tan\left(\Delta\sqrt{1-b}\right) = \frac{\frac{n_g^2}{n_s^2}\sqrt{\frac{b}{1-b}} + n_g^2\sqrt{\frac{b+a}{1-b}}}{1 - \frac{n_s^2}{n_g^4}\sqrt{\frac{b(b+a)}{1-b}}} \quad (3)$$

where Δ stands for the thickness of the gold slab, n_g is the refractive index of gold, n_s that of the substrate, $a = (n_s^2 - 1)/(n_g^2 - n_s^2)$ is defined as the asymmetry measure and $b = (\beta^2/k_0^2 - n_s^2)/(n_g^2 - n_s^2)$ is the normalized mode index.

The resonant frequencies of both antennas can then be obtained by combining the respective dispersion relations (1) and (3) with the resonance condition (2). Furthermore, they can also be calculated by numerical simulation [12], measuring the frequency for which the numerically calculated absorption cross section of the antenna is maximized.

After solving the dispersion relations of graphennas and metallic nano-antennas, we find that their resonant frequencies show a very different behavior in the frequency range of interest. Figure 2 compares the resonant frequency of graphene and metallic nano-antennas as a function of their length. The antennas are modeled as simple free-standing rectangular patches without dielectric substrate; in the case of metallic (gold) antennas,

FIGURE 2. Scalability of the resonant frequency of graphene (blue line) and metallic (yellow line) nano-antennas as a function of their length. The simulation results for graphene (stars) and metallic (crosses) antennas are also shown.

we assume a thickness of $\Delta = 20$ nm, in agreement with recent experimental works [13]. The blue line shows the first resonant frequency of a graphenna, as obtained from equation (1), while the yellow line corresponds to the resonance of a metallic nano-antenna, calculated by means of its respective dispersion relation (3).

We observe that, in the terahertz range, not only the resonant frequency of a graphenna is more than one order of magnitude lower than that of a metallic nano-antenna with the same size, but also the scalability of the antenna resonant frequency as a function of its length is very different. It can be found by curve fitting that the resonant frequency of a metallic nano-antenna f_{0Au} is inversely proportional to its length in the considered frequency range. In a graphenna, however, we observe a different trend; its resonant frequency f_{0gr} scales inversely proportional to the square root of the antenna length:

$$f_{0Au} = \Theta\left(\frac{1}{L_{eff}}\right) \qquad f_{0gr} = \Theta\left(\frac{1}{\sqrt{L_{eff}}}\right). \quad (4)$$

Interestingly, the scalability of the resonant frequency seen in graphennas is also different from the behavior observed in plasmonic nano-antennas made of noble metals and operating in the optical domain, whose resonant frequency is inversely proportional to the antenna length [14–16]. Indeed, their unique scalability trend turns out to be one of the strongest factors that motivate the use of graphennas to implement wireless communications among nanosystems. Indeed, as the graphenna size is reduced, its resonant frequency increases at a slower pace as compared to a metallic nano-antenna. For instance, as shown in Figure 2, metallic nano-antennas with a length of 1 µm resonate at a frequency of 150 THz, in the short-wavelength infrared range. By comparison, a

quency of only 3.8 THz, almost two orders of magnitude below a metallic nano-antenna. In short, this study confirms that graphennas of micrometric size will be able to radiate electromagnetic waves in the terahertz band, at a much lower frequency and therefore with a higher transmission range than equivalent metallic nano-antennas.

Moreover, the obtained dependences for the resonances of graphene and gold antennas have been validated by numerical simulation. Graphennas are modeled as a free-standing graphene patch with an infinite width. Graphene is characterized as an equivalent surface impedance [6], with a conductivity obtained with a Drude model. On the other hand, metallic nano-antennas are modeled as a free-standing thin gold slab with an infinite width and a thickness of 20 nm. The conductivity of gold was also obtained with a Drude model.

In Figure 2, the crosses show the simulation results of the resonant frequency of graphennas with a length ranging from 50 nm to 1 mm. The penetration length δL has been estimated as a 15% of the antenna length, based on the numerical simulations. The same results for metallic nano-antennas are shown as stars. As it can be observed, in both cases the simulation results show a very good agreement with the resonant frequencies obtained by solving the respective dispersion relations. Moreover, the simulations allow measuring the evolution of the antenna resonant frequency in the regions where the numerical results diverge from the scalability trends observed by solving the dispersion relation. In particular, as it can be seen in Figure 2, the scalability of the resonant frequency of graphennas with a length larger than 100 μm is no longer $f_{0gr} = \Theta\left(1/\sqrt{L_{\mathrm{eff}}}\right)$, but it tends to converge with the behavior observed in metallic antennas. Moreover, for metallic nano-antennas with a length smaller than 0.2 μm, as the resonant frequency reaches the threshold at which SPP waves start appearing in gold, its value starts diverging from the scalability trend $f_{0Au} = \Theta\left(1/L_{\mathrm{eff}}\right)$ observed for lower frequencies.

To conclude, we have analyzed the scalability of the resonant frequency in graphene-based plasmonic nano-antennas (*graphennas*) and metallic nano-antennas as a function of their length, for sizes ranging from 50 nm to 1 mm. We have obtained the resonant frequency in these antennas by combining the dispersion relation in a free-standing graphene layer and a gold slab, respectively, with the antenna resonance condition. Moreover, we have validated these results by numerical simulation.

The obtained results demonstrate that micrometer-sized graphennas resonate in the terahertz band, consistently with theoretical predictions [5]. More importantly, we have found that the resonant frequency in graphennas increases more slowly than in metallic nano-antennas as the antenna length is reduced. In particular, the derived scalability trends show that, when consid-

quency of graphennas is up to two orders of magnitude lower than that of metallic nano-antennas with the same size.

These results open up the possibility to implementation of wireless communication among nanosystems by means of graphennas with dimensions of a few μm, thereby enabling the novel paradigm of graphene-enabled wireless communications.

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... However, they suffer from poor antenna performance like low bandwidth, low gain, and very low radiation efficiency when scaled down to micrometer range because of the low conductivity and low mobility of nanoscale metallic antennas [13]. Besides, miniaturizing metallic microstrip antennas down to few micrometers causes them to radiate near the optical frequency range of several hundreds of terahertz [14] , which makes metallic nanoscale antennas practically unusable due to very high channel attenuation and infeasibility to design transceiver of such high-frequency operation. ...

... As with the case of increasing air gap diameter, a stopband arises form 5.62 THz to 5.84 THz for hexagonal shape. For the 14 same side length, the hexagon has a bigger air volume compared to other two shapes, which agrees with the increase of air volume when the diameter of the cylindrical air gap was increased from 4 μm to 8 μm. From Fig. 13(b), we can see that there is no significant change in antenna radiation efficiency or antenna gain due to the different shapes of the air holes. ...

High-gain and ultrawide-band graphene patch antenna with photonic crystal covering 96.48% of the terahertz band

Preprint

Nov 2020

Md. Abdul Kaium Khan · Ibrahim Ullah Emon · Mohammad Abdul Alim

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... The special dispersion relation induced plasmonic resonance of graphene is in the THz range [3], and thus of increasing interest in short-range communications [4]. Graphene excels its metallic counterparts since the antennas are up to two orders of magnitude smaller in area, as predicted by simulations [5] . Material parameters such as the relaxation time and the chemical potential , are crucial for the adequate functionality (e.g. ...

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... Graphene, a pioneer of two-dimensional (2D) materials, has superior electrical, thermal, mechanical and electromagnetic properties, which opened the door to emerging applications in electronics and communications at the micro-and even nanoscales [7][8][9][10][11][12]. In particular, the very high charge density and excellent mobility of charges [13] offers new perspectives for designing the next generation of non-metallic electronic devices, which require superior performance, small size and easy mutualisation, while the mechanical properties suggest an attractive potential for flexibility and wearability [14][15][16][17][18]. Theoretical calculations have suggested that optical and terahertz graphene antennas can resonate at frequencies much lower than their metallic counterparts [19] [20][21][22]. In parallel, the utilization of graphene for microwave antenna technology has been explored in a number of experimental works, which focused on the development of simple graphene fabrication techniques with low manufacturing cost and possible scale-up for mass industrial applications [23][24][25][26][27][28][29][30][31][32]. ...

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... It is well known that graphene naturally supports Surface Plasmon Polaritons (SPP) in the terahertz band, and therefore, becomes an excellent option for the implementation of terahertz sources [26] and antennas [27], among others. The plasmonic nature of graphene at terahertz frequencies leads to miniaturized devices [28] , whereas its inherent tunability has been leveraged in frequency-agile or reconfigurable concepts [29]- [31]. Some of such designs are array-based, and similar to programmable metasurfaces, they achieve reconfigurability by switching the state of its elements, i.e. tuning them in or out [32]- [34]. ...

Digital Metasurface Based on Graphene: An Application to Beam Steering in Terahertz Plasmonic Antennas

Preprint

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... Besides, miniaturizing metallic microstrip antennas down to few micrometers causes them to radiate near the optical frequency range of several hundreds of terahertz [14] , which makes metallic nanoscale antennas practically unusable due to very high channel attenuation and infeasibility to design transceiver of such high-frequency operation. The metallic antennas are also vulnerable to micro-cracks [15,16]. ...

High-gain and ultrawide-band graphene patch antenna with photonic crystal covering 96.48% of the terahertz band

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... The resonant frequency of the graphene patch antenna is calculated is based on the condition of resonance of the antenna combined conventional patch by the SPP wave dispersion relation and it is given by (Llatser, Kremers, Cabellos-Aparicion, & Alarcón, 2012) : ...

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... It is well known that graphene naturally supports Surface Plasmon Polaritons (SPP) in the terahertz band, and therefore, becomes an excellent option for the implementation of terahertz sources [26] and antennas [27], among others. The plasmonic nature of graphene at terahertz frequencies leads to miniaturized devices [28] , whereas its inherent tunability has been leveraged in frequency-agile or reconfigurable concepts [29]- [31]. Some of such designs are array-based, and similar to programmable metasurfaces, they achieve reconfigurability by switching the state of its elements, i.e. tuning them in or out [32]- [34]. ...

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... After its discovery, Graphene [6] has shown lot of potential applications in several important areas owing to its remarkable physical, mechanical and electrical properties. Use of Graphene in antenna applications is, however, a relatively new direction [7] with the advent of micro and nano sized antennas based on Graphene, "Graphenna" [8, 9]. Especially at the THz band, the main advantages of Graphene over metals for antenna applications are: (a) Graphene supports transverse magnetic (TM) resonant surface plasmon polariton (SPP) modes even at lower THz frequencies unlike their noble metallic counterparts [10], (b) the electron mobility in Graphene, even at nano-dimensions is about 10 5 times higher than that in copper [11], (c) the current carrying capacity of Graphene is almost 2-3 orders of magnitude higher than metals, (d) the electrical characteristics of Graphene can be varied dynamically presenting potential for plethora of applications. ...

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February 2016 · Chinese Physics Letters

Liu Zhi-Kun · Xie Ya-Nan · Geng Li · [...] · Song Pan

We present a surface current method to model the graphene rectangular nanoantenna scattering in the terahertz band with Comsol. Compared with the equivalent thin slab method, the results obtained by the surface current method are more accurate and efficient. Then the electromagnetic scattering of circularly polarized terahertz waves on graphene nanoantennas is numerically analyzed by utilizing ... [Show full abstract]

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Graphene-based Nano-patch Antenna for Terahertz Radiation

October 2012 · Photonics and Nanostructures - Fundamentals and Applications

Ignacio Llatser · Christian Kremers · Albert Cabello · [...] · Dmitry N. Chigrin

The scattering of terahertz radiation on a graphene-based nano-patch antenna is numerically analyzed. The extinction cross section of the nano-antenna supported by silicon and silicon dioxide substrates of different thickness are calculated. Scattering resonances in the terahertz band are identified as Fabry–Perot resonances of surface plasmon polaritons supported by the graphene film. A strong ... [Show full abstract]

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Scattering of Terahertz Radiation on a Graphene-based Nano-antenna

October 2011

Christian Kremers · Albert Cabello · Dmitry N. Chigrin · [...] · Ignacio Llatser Marti

Scattering of the terahertz radiation on a graphene-based nano-antenna is considered. Different electromagnetic models of graphene are discussed and applied to calculate extinction, scattering and absorption cross sections of the nano-antenna. Scattering resonances in the terahertz band are identified as longitudinal Fabry-Perot resonances of surface plasmon polaritons supported by the graphene ... [Show full abstract]

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Characterization of Graphene-based Nano-antennas in the Terahertz Band

March 2012

Ignacio Llatser · Christian Kremers · Dmitry N. Chigrin · [...] · Eduard Alarcón

Graphene-enabled wireless communications constitute a novel paradigm which has been proposed to implement wireless communications at the nanoscale. Indeed, graphene-based nano-antennas just a few micrometers in size have been predicted to radiate electromagnetic waves at the terahertz band. In this work, the performance of a graphene-based nano-patch antenna in transmission and reception is ... [Show full abstract]

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December 2012 · Radioengineering

Ignacio Llatser · Christian Kremers · Dmitry N. Chigrin · [...] · Eduard Alar On

Graphene-enabled wireless communications constitute a novel paradigm which has been proposed to implement wireless communications among nanosys-tems. Indeed, graphene-based plasmonic nano-antennas, or graphennas, just a few micrometers in size have been predicted to radiate electromagnetic waves at the terahertz band. In this work, the important role of the graphene con-ductivity in the ... [Show full abstract]

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